Medium access control schemes for flat mobile wireless sensor networks

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Medium Access Control Schemes for Flat Mobile Wireless Sensor Networks

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***Abstract* - One aspect of Mobile Wireless Sensor Networks (MWSNs) is the MAC protocol, which is critical in terms of reliability, delay and energy consumption. This work begins with a literature review, showing that the majority of MWSN MACs are designed for hierarchical architectures, demonstrating that there is a lack of MACs intended for flat architecture MWSNs. Subsequently, we propose three new MAC protocols, uniquely designed for flat MWSNs. Explicitly, the proposed MACs are Carrier Sense Multiple Access with Dedicated Slots, Network Division Multiple Access with Collision Avoidance and Network Division Multiple Access with Dedicated Slots, which are specifically designed to work with the state-of-the-art Location Aware Sensor Routing protocol. Extensive modelling and simulation is done in dense and sparse scenarios with varying traffic levels to evaluate the impact of the proposed from the perspective of both the link and network layers. Given the uniqueness of the proposed protocols, four well-known MACs are also included to give a performance reference to the results. The MAC results show that the collision-free protocols give the best reliability and that Global-TDMA consistently yields the highest level of throughput. This highlights the importance of taking into account both MAC and routing during the design process.**

1. Introduction

Mobile wireless sensor networks (MWSNs) are designed to gather data in the most challenging and dynamic environments. These networks generally consist of multiple nodes, that have the ability to take an input from a sensor, such as light, sound, humidity or pressure. They are also equipped with transceivers, to enable them to transmit and receive messages between each other wirelessly. Contrary to statics wireless sensor networks (WSNs), MWSNs have some form of mobility platform, which may be a manned or unmanned vehicle, a person or an animal. This makes them highly applicable to many scenarios and situations. Applications of these networks include wildlife tracking, search and rescue, security and smart cities [1]. Additionally, sensor networks may be connected to the internet to contribute to the internet of things.

One key issue in these kinds of networks is that of routing and medium access control (MAC) [2]. The routing protocol is designed to pass the sensed data through the network to a sink. It is the responsibility of the MAC to govern when the sensor is permitted to transmit wirelessly. In this way the MAC protocol can attempt to prevent multiple nodes transmitting at the same time, which can cause collisions, making the data unreadable. In the case of a collision, the data will often need to be retransmitted, using up additional resources. As such, a correctly designed MAC can save energy, decrease data delivery time and provide a more reliable communications system. In a MWSN the movement of nodes makes both MAC and routing a difficult task. With routing, a dynamic topology means that there is no permanent or guaranteed path from the sensor to the sink. Additionally, for

MAC protocols, not knowing the topology makes scheduling nodes to transmit without collisions a complex task. Both MAC and routing protocols need to be reliable, efficient and also use a minimal amount of energy.

In static WSNs, it is common to employ a hierarchical architecture, in which one node in a cluster is designated the cluster head. Sensor nodes then report data to their cluster head, whose role it is to relay that data back to the sink [3]. Contrastingly, networks that assign every node the same role are considered to be using a flat architecture. As will be shown in the next section, much of the literature concerning MACs designed specifically for MWSNs, is orientated around on adapting protocols that were originally designed for static sensor networks [2]. Therefore the majority of proposed protocols primarily focus on using sleep scheduling to conserve energy in static networks with a hierarchical architecture. Whilst these are useful in many circumstances, there are still many applications that do not lend themselves to a cluster based approach and in which low delay times are more important than conserving energy. Such applications include drone aided search and rescue, in which the swarm is deployed to an unknown area and expected to report data back to a manned team in a helicopter. The fact that each node is expected to be a data source and the entire network is mobile, makes it more suited to a flat routing protocol that can handle the frequent topology changes without the overhead of establishing clusters that are not expected to last very long. Additionally, the high mobility levels of all nodes make the optimal selection of cluster heads a difficult task.

For this reason, this work considers the case of MWSNs with a flat architecture, in which energy conservation is not the main aim. Though it should be noted that energy is still an issue and should aim to be reduced where possible. Furthermore, for evaluation purposes, the recently published flat MWSN routing protocol, LASeR (Location Aware Sensor Routing) [4], will be used to give realistic design and simulation results. LASeR is opportunistic, geographic protocol that yields high reliability and low end-to-end delays. As such it was chosen as a likely candidate to be used in networks that value speed and consistency rather than power limiting.

This work firstly acknowledges the shortage of MAC solutions designed specifically for MWSNs with flat architectures and highlights this as a gap in the existing literature. In response to this three novel MAC solutions are proposed, that are designed explicitly to be used in conjunction with a flat routing protocol. Since the MAC and routing are expected to work in harmony with each other, the suggested MAC protocols are developed with the recently published LASeR protocol in mind. This consideration during the design process is critical to the realisation of highly optimised systems. Results are gathered through simulation for the proposed schemes and reference results from the literature are also included. Both MAC layer and routing layer metrics are used to evaluate the performance of the MAC protocols and also their effect on the routing, which gives a more realistic impression of the impact of the MACs.

2. Related Work

In this section existing MAC protocols designed explicitly for MWSNs will be identified. One such MAC is MS-MAC [5], which is based on the static WSN MAC, SMAC (Sensor MAC) [6]. MS-MAC uses the periodic sleep schedule proposed for SMAC but in a dynamic way, whereby nodes synchronise their schedules periodically. In order to account for varying rates of topology change, the frequency of the synchronisation is determined based on the level of mobility in a neighbourhood. The nodes sample RSSI (Received Signal Strength Indicator) values by measuring the power levels of the packets from their neighbours and use this to determine their level of mobility, subsequently, high mobility causes the nodes to update their schedules more frequently.

Another protocol based on SMAC is MOBMAC [7], which attempts to improve the performance of SMAC by reducing the amount of frame loss due to the Doppler shift in transmissions from a mobile source. This is done by varying the frame size, such that in bad channel conditions only small frames are transmitted and in good channel conditions larger frames are permitted. This means that in bad channel conditions any losses are kept to a minimum and good channel conditions are taken advantage of by transmitting more data.

MS-SMAC [8] is similar to MS-MAC in its scheduling, however it requires the use of known static nodes to transmit messages to the mobile nodes, such that the mobile nodes can determine their speed more accurately. In this way it allows mobile nodes to indicate to its neighbours when its speed has changed and then update the synchronisation frequency accordingly. Each node also records how long it's expecting to be able to talk to each of its neighbours.

Similarly, MobiSense [9] also uses static nodes; in this case the static nodes are intentionally placed cluster heads which form the backbone of the network. Adjacent clusters are required to communicate in different channels, such that they can reduce inter-cluster interference and schedules can be efficiently designed locally by the cluster head. MobiSense also uses regular broadcasts from cluster heads with information about their cluster including the channel number, such that nodes can move between clusters easily.

The cluster based MWSN MAC, MMAC [10], is based on TRAMA (Traffic Adaptive Medium Access) [11] protocol, which firstly allows each node to discover its two hop neighbours, then each nodes schedule is disseminated. The two hop neighbourhood, schedule and traffic information is then used to select transmitters and receivers for collision free communication. MMAC takes this idea and, using location awareness, predicts a nodes movements. This movement information is then used to adjust the frame size, such that high mobility causes shorter frames, which means that the topology information is updated more regularly.

Another MAC based on time synchronised scheduling is M_TDMA (Mobility-Aware TDMA) [12], which adapts a classical TDMA MAC for use in mobile scenarios. It does this by adding a control phase at the beginning of each round, in which a cluster head will broadcast the cluster information to its neighbour nodes. When a node hears this, it will know if it has moved clusters, is in the same cluster or is out of range of any cluster heads. If the node has moved clusters, it will then announce its presence to the cluster head, who will subsequently broadcast new time slot allocations. In the case of multiple nodes joining a new cluster, their announcements may collide, in which case they should initiate a random back-off timer and attempt to join the cluster in a later round.

Contrastingly, MA-MAC [13] is a low duty cycle protocol, which uses the short preamble of X-MAC [14], such that nodes can save time and energy. The short preamble contains the ID of the destination node and is strobed. This means that when a node wakes up and hears the preamble, if it is the intended destination then it can transmit an early acknowledgement before the preamble is retransmitted. The transmitting node can then follow this up by sending the data packet. MA-MAC improves on this system by including a handover mechanism, which reduces packet loss due to link breaks. During transmission, if the transmitter detects that the receiver is beyond a certain threshold, it will begin to look for potential relay nodes, which may then be used to pass on data to its intended recipient.

As an alternative to the schedule based MACs, MA-CSMA/CA (Mobility Adaptive Carrier Sense Multiple Access with Collision Avoidance) [15] takes the 802.15.4 MAC [16] for static WSNs and improves it for mobility. It does this by reducing the latency of the process by which mobile nodes may switch clusters. Nodes measure the signal strength of all the cluster heads in range and if one becomes stronger it is assumed that the node is moving towards it. At this point the node will request a time slot in the new cluster via its current cluster head. So the request is passed to the nodes cluster head, who then passes it to the cluster head that the node is moving towards. Once the new cluster head has received the request it allocates a contention free time slot for the node, which may then be used for association. After the time slot has expired the node reverts to the standard method of contending for the medium.

Similarly, from the same authors, CFMA (Collision Free Mobility Adaptive) [17] is also based on the 802.15.4 MAC. CFMA dictates that the cluster heads allocate a delay time to nodes, which is based on that nodes priority level. This allocated delay is used instead of the random back off that is normally performed in order to reduce collisions. Nodes that are moving clusters are given high priority and therefore a shorter delay time.

In conclusion, the existing sensor network MAC based literature is generally unsuitable for use with flat MWSNs. Whilst the reviewed protocols may perform well in their target applications, their main use is with a hierarchical architecture and aims to reduce energy consumption. Though the highly popular 802.11 DCF MAC [18] is still an option for flat MWSNs, as is the global time division multiple access (GTDMA) MAC presented in [4]. GTDMA allocates a single time slot to each node before deployment, the time slots cycle continuously with each node only transmitting in its own slot, making the network collision free. The time slots are allocated using an ID number, which indicates in which slot of the cycle that node should transmit. Since this is done before the network is deployed the time slot allocation remains constant throughout the mission. Due to the lack of existing MAC protocols for flat MWSNs, the following section will consider the development of new protocols for this scenario.

3. MAC Protocol Design and Development

Due to the widespread use of the clustering architecture and duty cycling in MWSN MAC protocols, most of the current literature is not ideally suited to a flat architecture. Subsequently, this section will investigate and propose some alternative solutions. Since the performance of a MWSN is heavily dependent on all layers working in harmony, this section will develop MAC protocols primarily for use with the flat MWSN routing protocol, LASeR. In this way the MACs can be optimised further to give the best performance.

LASeR is a geographic protocol that utilises each node’s knowledge of its physical position to maintain a gradient. The protocol then uses blind forwarding to propagate data through the network towards the sink. Blind forwarding is a technique where no specific forwarding node is selected, instead a transmitting node will broadcast the packet along with its distance from the sink. The transmitting node’s neighbours will overhear this broadcast and then decide whether to forward the packet by comparing the transmitting node’s distance from the sink with its own. This method of forwarding has low overhead and inherently creates multiple routes for each packet, which makes LASeR highly robust. In terms of a MAC layer, [4] selects a GTDMA protocol, in which nodes transmit in a predetermined timeslot, eliminating any potential collisions and also requiring no additional communications overhead.

3.1. Carrier Sense Multiple Access

It was previously mentioned that the 802.11 DCF MAC could potentially be used. This protocol uses the technique of carrier sense multiple access (CSMA) with collision avoidance (CA). The 802.11 DCF MAC dictates that if the channel is sensed to be busy then the node wishing to transmit should wait for a random amount of time before trying again. However, when used with LASeR, this mechanism will not be very successful. Due to LASeRs use of the blind forwarding technique, after a single transmission all of the overhearing nodes that decide to forward the received packet, will sense the medium. If the medium is sensed to be free by one, then it is likely that it will be sensed to be free by others. This will cause multiple nodes to forward the packet simultaneously, resulting in many collisions. The 802.11 DCF MAC also suggests the use of acknowledgements (ACKs) and a request to send (RTS), clear to send (CTS) handshake. These mechanisms also fail when used with LASeR. The ACK is used by the intended next-hop receiving node to indicate to the transmitting node that the packet was received successfully. However in LASeR, there is no single intended node. This means there may be more than one receiving node, in which case there is a high chance that multiple nodes will reply with ACKs. The multiple ACKs are highly likely to collide, which means it will not be received by the transmitting node and could cause the packet to be retransmitted unnecessarily. Similarly, as there is no intended path in LASeR, a RTS/CTS handshake cannot take place. If a RTS is broadcast, multiple nodes may respond with a CTS, causing collisions. Additionally, the responding nodes may not even be neighbours who will then decide to forward the packet. From this point the 802.11 DCF MAC without ACKs or RTS/CTS handshakes, will simply be referred to as CSMA/CA.

3.2. Dedicated Channel Sensing Slots

Developed from the CSMA/CA MAC, one novel technique proposed here is the use of dedicated channel sensing slots (CSS), in which the node will perform a clear channel assessment (CCA). This is a compromise between the CSMA/CA technique with a GTDMA and is referred to as CSMA/DS (CSMA with Dedicated CCA Slots). Each node is allocated a small slot in which to sense the medium. If the medium is sensed to be free the node may then transmit. The transmission will then cause the medium to appear busy to the nodes with subsequent CCA slots. The frame structure is shown in figure 1, which illustrates how the nodes all have sufficient time to sense the medium in their own slot and then transmit a packet. It can also be seen how a node with an earlier time slot may use the medium and essentially block transmissions by other nodes. This prevents any local collisions within a node's neighbourhood from two nodes simultaneously sensing the medium to be free. As such it essentially replaces the RTS/CTS handshake, however the hidden and exposed node problems may still occur. It should also be noted that no ACKs or RTS/CTS handshakes are used in the CSMA/DS MAC. The size of the CSS will be dependent on the time needed to perform a CCA, which is dictated by the hardware used.

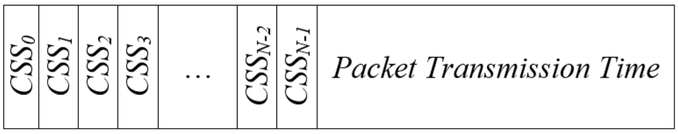


Fig. 1. CSMA/DS frame structure, where CSS_n is the channel sensing slot for node n in a network of N nodes. Essentially, node *i* will sense the medium in CSS_i and if the medium is clear the node will transmit, else it will wait for the next opportunity. The overall frame size must be large enough that after node *N-1* senses the medium it still has time to complete a packet transmission before the next frame begins.

Figure 2 gives the flow chart for CSMA/DS, which outlines the protocols basic decision making process. When the MAC layer receives some data from the routing layer it is put in a queue. The MAC protocol will then wait until its own dedicated sensing slot, before listening to the channel. If the channel is free the data can be sent, otherwise the transmission will be deferred until the next frame.

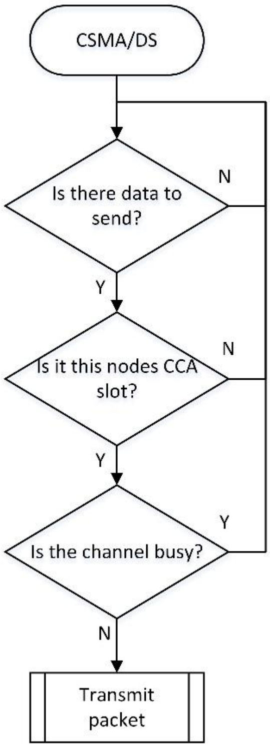


Fig. 2. CSMA/DS protocol flow chart.

3.3. Network Division Multiple Access

Since LASeR and other MWSN routing protocols and applications use location awareness, this information could be utilised by the MAC layer a network division multiple access (NDMA) scheme is proposed. This technique divides the network area into cells such that spatial reuse can take place to increase efficiency. The NDMA method introduced here is similar to the location aware MAC protocol (LAMP) proposed in [19]. In the implementation presented here groups of non-interfering cells take it in turn to be active. If a node is in an active cell then it may contend for the medium. Figure 3 illustrates how the network may be split up in to cells, labelled *A* to *P*. The letters correspond to the order in which the cells are active, such that all of the cells with the same letter maybe active at the same time.

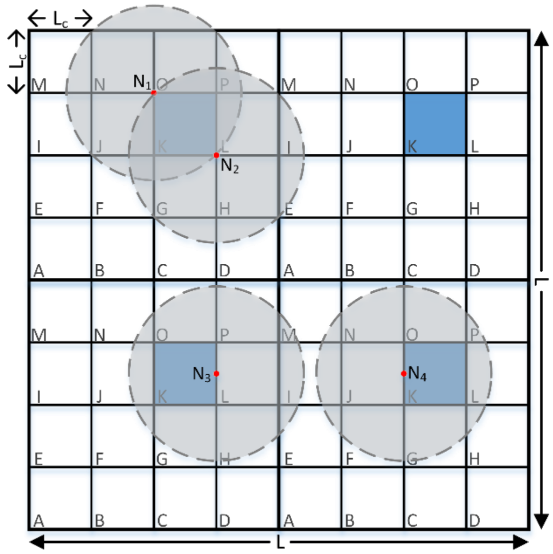


Fig. 3. NDMA network area split into cells, where L is the length of the area and L_c is the length of a single cell. Nodes a denoted as N_i where i is their node number.

In figure 3 the two constraints for the cells size are shown. In the figure the highlighted *k* cells are active. The first constraint is that every node in the cell should be able to hear every other node in the same cell. Such that, when one node is transmitting the other nodes in the cell can hear it and defer their own transmissions. This means that the diagonal length of the cells must be less than the transmission radius, *r*, so the height of a cell, L_c, must satisfy $L_c < r/\sqrt{2}$, as shown by nodes N_1 and N_2. The second constraint is that the transmissions from two nodes in different active cells should not collide. So active cells should be more than $2r$ apart, in other words, active cells must have at least $2\sqrt{2}$ cells between them, as illustrated by nodes N_3 and N_4.

Since nodes in the active cells will have to compete between each other for the medium, NDMA cannot be used alone. It is therefore suggested to use the collision avoidance mechanism from the CSMA/CA MAC layer. This protocol will be referred to as NDMA/CA. NDMA/CA allows nodes in active cells sense the medium and if it's free they may transmit. If the medium is sensed to be busy a back off counter is started, such that if the timer expires and the cell is still active, the node may try again. Alternatively, NDMA may be used with dedicated CSS slots (NDMA/DS), in which nodes in active cells use their allocated slot to sense the medium. If it's free they may transmit, otherwise they will have to wait until the cell becomes active again. The use of NDMA eliminates the hidden node problem and local collisions are avoided with the dedicated CCA slots, NDMA/DS is collision free.

Figure 4 gives the high level flow charts for both NDMA/CA and NDMA/DS. The flow chart for NDMA/CA in figure 4a, shows how upon receiving data, the MAC layer first waits until it’s in an active cell. It will then sense the medium and if the medium is clear the data may be transmitted. If the medium is sensed to be busy the back off timer will be set. Subsequently, whilst the node remains in the active cell, the back off timer will be decremented until it has expired. At which point the node will transmit the data.

Similarly, NDMA/DS begins by checking whether the node is in an active cell, as shown in figure 4b. If it is, then the node will wait until its dedicated sensing slot before listening to the medium. If the channel is sensed to be clear then the transmission can be sent, otherwise it will be deferred.

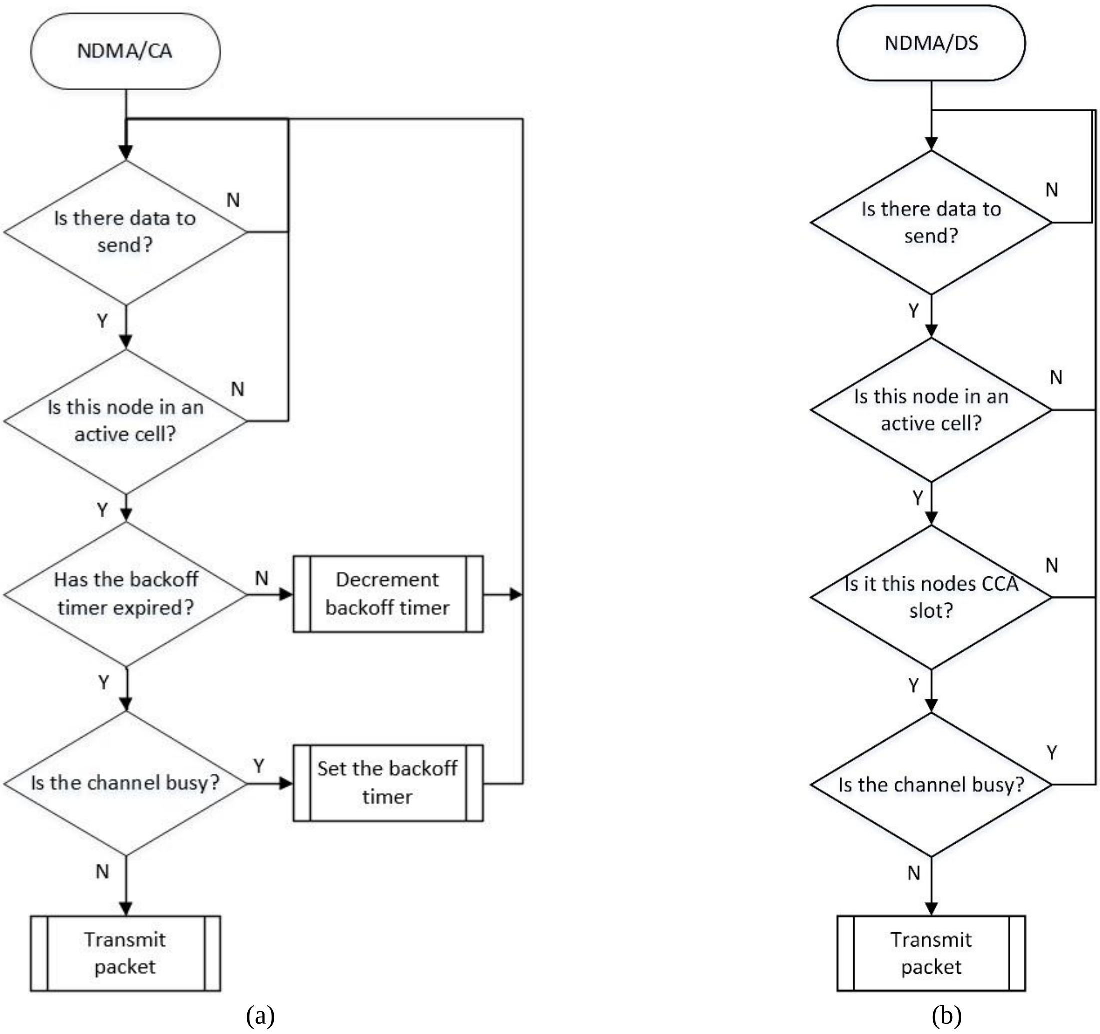


Fig. 4. Protocol flow charts for a) NDMA/CA and b) NDMA/DS.

Based on the literature review in the previous section and the proposed protocols, further results will be gathered for LASeR with the GTDMA MAC, CSMA/CA, CSMA/DS, NDMA/CA and NDMA/DS. Additionally, to give a baseline performance level, a slotted ALOHA (SA) MAC will also be simulated, as will slotted ALOHA with CCA based collision avoidance (SA/CA). The SA/CA MAC allows any node with data to sense the medium and then send the packet. If the medium is sensed as busy, then there is no back off, the node simply tries to transmit in the next slot. Results for more recent MWSN

MAC protocols, as reviewed in section 2 will not be evaluated through simulation, since they are not compatible with a flat architecture.

4. Modelling and Simulation

In order to evaluate the selected MAC protocols, they will be used with LASeR in the popular OPNET [20] simulator. The network will be evaluated in two ways; focusing first on the performance of the MAC layers and secondly on the performance of the network from the point of view of the routing. In this way, the isolated MAC layers may be analysed as well as their impact on the MWSN as a whole.

The MAC layer metrics used will be packet delivery ratio (PDR), average queuing delay, collision ratio, throughput and total number of collisions. The routing level metrics used will be PDR, average end-to-end delay, average overhead, throughput and energy consumption.

The MAC PDR is defined as the ratio of successfully received packets to the total number of potential packet receptions. The average queuing delay is the average length of time a between a packet being received and it being forwarded. The collision ratio is the total number of collisions over the total number of possible packet receptions. MAC throughput is defined as the number of bits per second successfully received by a node. Lastly, the total number of collisions is the sum of all the collisions that occurred over the simulation time.

The routing PDR is the ratio of packets received at the sink over the total number of packets created. The average end-to-end delay is the average time between a packet being created and it being delivered at the sink. The average overhead is defined as the ratio between the total number of bits transmitted and the number of successfully delivered data bits. The routing throughput will be taken as the total number of data bits successfully delivered to the sink, per second. Average energy consumption focuses on the power used by communications only, and is therefore measured as the total energy used to receive and transmit messages, averaged over the number of nodes.

The results are gathered for two scenarios; the first is a dense scenario, in which *25* nodes are deployed in a *600m* by *600m* area. Each node can transmit at *250kbps* and has a transmission range of *250m*, which is similar to the rate and range of the Memsic IRIS motes [21]. This means that each node's communication coverage will be at least 14% of the entire network area. In order to focus the results on the effect of the MAC and routing layers, the effects of the physical channel are omitted. The traffic levels are varied in this scenario by adjusting the per node packet generation rate to *[0.1, 1, 5, 10]packets per second* (pk/s). This represents network data generation rates of between *2.4pk/s* and *240pk/s*.

The second scenario also uses *25* nodes, but they are deployed in an area of *1500m* by *1500m*, to represent a sparse network. The transmission rate and range are kept constant at *250kbps* and *250m* respectively. The packet generation rate is set to *0.1pk/s*, but the packet data size is varied at *[32, 256, 4096, 65536]bits*. In both scenarios all sensor nodes are mobile and are controlled by a random waypoint mobility model, which uniformly selects a speed of between *0* and *25m/s*.

5. Results

The results in figure 5 show the performance of the various MAC protocols in the first scenario as the traffic level is varied. Unsurprisingly, the collision free MACs, GTDMA and NDMA/DS achieve 100% PDR, with CSMA/DS also achieving a high level of success. CSMA/CA and NDMA/CA show a medium level of delivery success with the two ALOHA based MACs yielding the lowest PDR. The inverse of this is shown as collision ratio, with both GTDMA and NDMA/DS causing no collisions. The delay results for every MAC show a steep decline between *0.1pk/s* and *1pk/s*, this is due to the queue size; with a low packet generation rate, each node can store every packet that's received and it takes time to transmit them all. However, as the packet generation rate increases, each node will receive more packets and the length of the queue will be exceeded, with the older packets being dropped in favour of newer ones. This allows newer packets to be transmitted faster since they don't have to wait for older ones to be serviced first. In LASeR, this loss of older packets is not a problem as the multipath nature of the protocol makes it highly likely that the dropped packets will be delivered by another node. This will be highlighted by the PDR levels shown in the routing results given later. Overall, NDMA/DS and NDMA/CA give the worst delay performance, since nodes have to wait for their cell to be active and then for the medium to be free. The ALOHA based MACs give the best delay, but this is due to their short service times and their low delivery rates, which means that many packets are dropped and allows the successful packets to be delivered faster. In comparison, GTDMA and CSMA/DS have both very low delay and very high PDR. The throughput results show GTDMA to consistently have the highest throughput, with CSMA/DS just behind it. CSMA/CA shows a reasonable level of throughput, however the other four MACs are significantly lower due to low PDR in the case of SA and SA/CA or high delay in the case of NDMA/CA and NDMA/DS. The total number of collisions show that both GTDMA and NDMA/DS are collision free. CSMA/CA has the highest number of collisions, however because it transmits a lot of packets its collision ratio remains relatively low. Contrastingly, SA and SA/CA show a lower number of collisions but a higher collision ratio, which implies that they transmitted less packets, but more of them were involved in collisions.

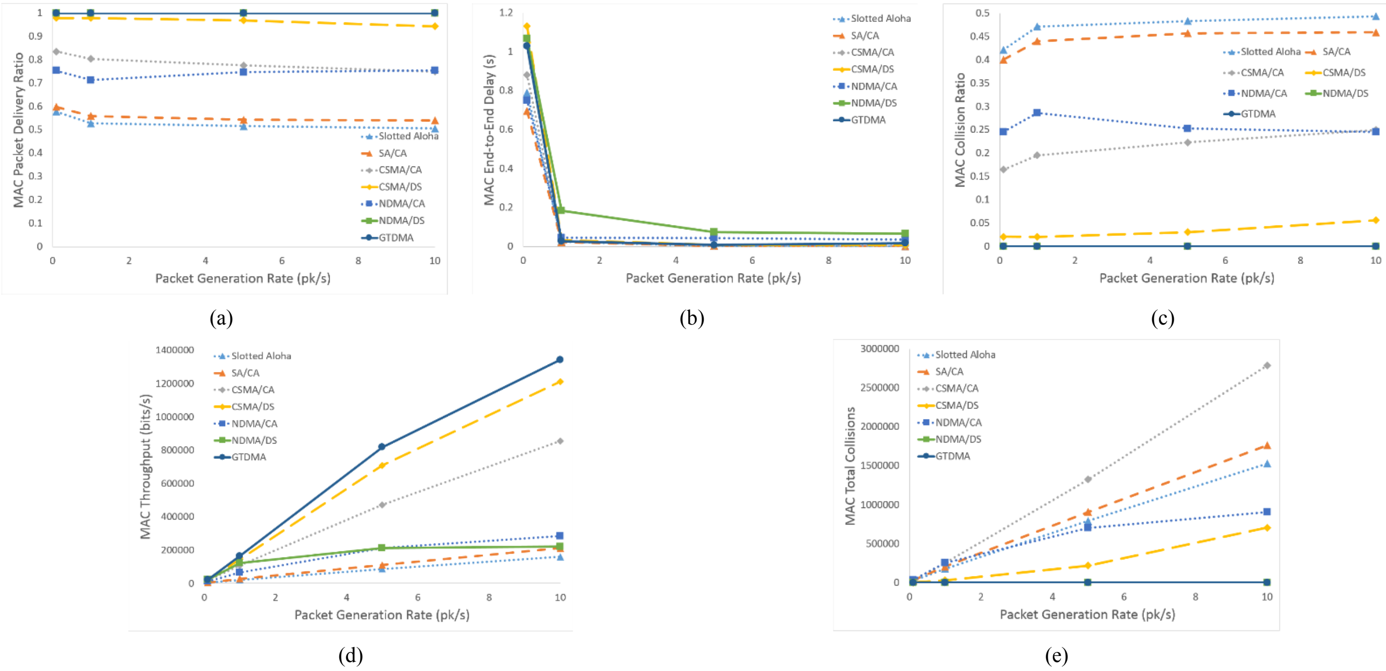
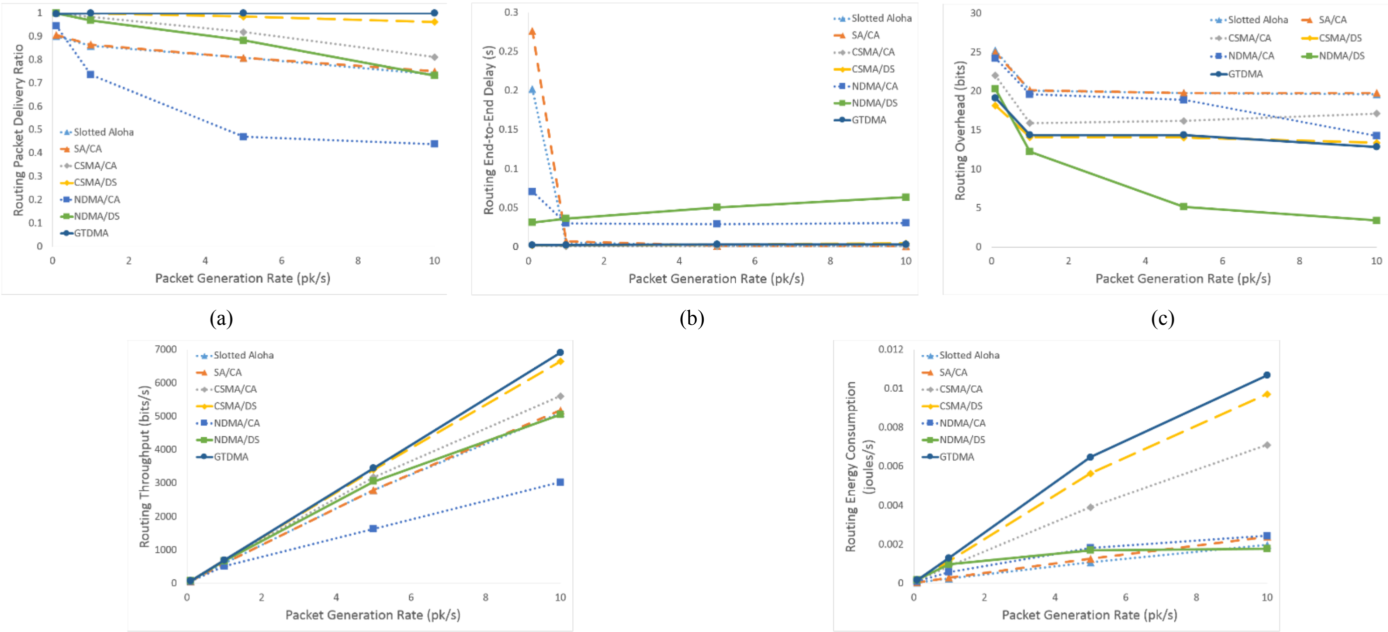


Fig. 5. MAC results using the selected MAC protocols, for varying traffic levels: (a) PDR, (b) Average end-to-end delay, (c) Collision ratio, (d) Throughput and (e) Total number of collisions.

The routing results given in figure 6 were collected at the same time as the MAC results in figure 5. The routing PDR shows the GTDMA MAC to have the best performance, with CSMA/DS also being very high, which is similar to the MAC PDR results. However, NDMA/DS gives worse results, which is mostly due to it having the worst routing delay characteristics. This trend is also true of NDMA/CA. This occurs because the high MAC layer delay is only typical of a single hop and, since LASeR is a multihop routing protocol, this high delay is amplified as packets experience more hops, which eventually causes packet loss. Contrastingly, GTDMA and CSMA/DS give very low routing delay. Similarly to the MAC results, SA and SA/CA also give low delay due to their low level of PDR. LASeRs overhead is generally low for all MAC protocols, with NDMA/DS having the lowest. This is due to its high MAC delay time, which means that it is taking a long time to transmit packets and therefore transmissions occur less often, so less redundancy is created. In terms of throughput, NDMA/CA is the worst, since it has low PDR and high delay. GTDMA and CSMA/DS have the highest level of throughput, but at the cost of high energy consumption. The lower PDR of the other protocols are reflected in their energy consumption.



(a) (b) (c)

(d) (e)

Fig. 6. Routing results using the selected MAC protocols, for varying traffic levels: (a) PDR, (b) Average end-to-end delay, (c) Overhead, (d) Throughput and (e) Average energy consumption.

The MAC results for the second scenario are shown in figure 7, which highlight the sparse nature of the scenario, with all the MAC layers showing very high PDR. As in the first scenario, the collision free MACs give the best PDR, with CSMA/DS just behind. Again CSMA/CA and NDMA/CA are in the middle, with SA and SA/CA at the bottom. The MAC delays also show a significant increase in comparison to the first scenario, which is due to the additional time needed to transmit the longer packets. As such, the GTDMA MAC is now one of the worse and the SA and SA/CA MACs still have the lowest delay due to their short service time and low PDR. As with the PDR results, the collision ratio results follow a similar pattern to those of the first scenario, with the ALOHA based schemes having the highest ratio, followed by CSMA/CA and NDMA/CA. Then the CSMA/DS MAC and finally GTDMA and NDMA/DS having no collisions. This hierarchy is also reflected in the results for the total number of collisions. The MAC throughput results show GTDMA to be the highest, with NDMA/DS close behind and CSMA/DS not far behind that.

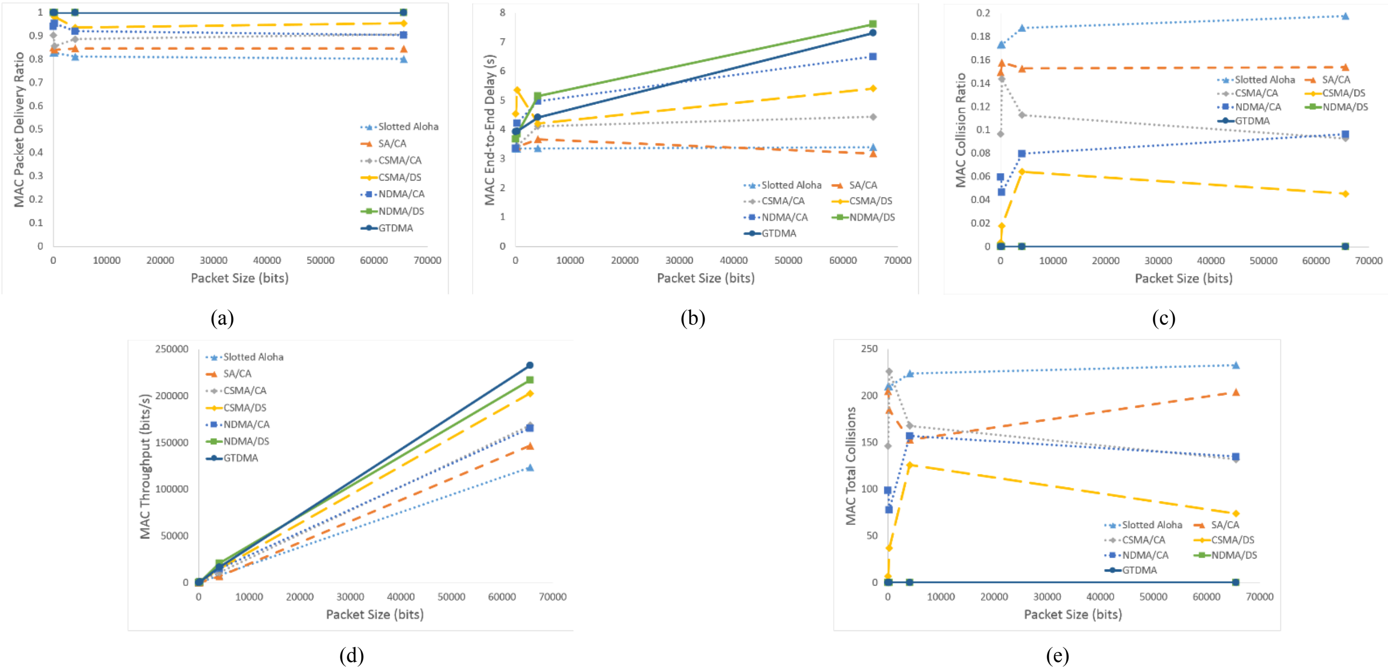


Fig. 7. MAC results using the selected MAC protocols, for packet sizes: (a) PDR, (b) Average end-to-end delay, (c) Collision ratio, (d) Throughput and (e) Total number of collisions.

Figure 8 shows the routing results for the second scenario, which show a very low PDR for all MACs, which is in direct contrast to the MAC PDR results in the same scenario. This is mostly due to the significant increase in routing delay, which is also a product of the sparsity of the scenario. The NDMA/DS MAC has the best PDR as the packet size increases, which is because the relative size of the CCA time to the packet transmission time decreased: In very small packet scenarios, the CCA time may be comparable to the time taken to transmit a packet. In such cases it is beneficial to allocate time slots, such that significant time isn't wasted checking the medium, which may return false or yield a false positive in the event of a hidden node and adding further delay. However, as the packet size increases, the CCA time becomes insignificant in comparison to the transmission time of a packet. In this case, the duration a node must wait in a time slotted scheme is far greater than that of a node which checks the medium and then transmits. Given this improved delay characteristic and high MAC PDR, NDMA/DS gives the best routing PDR result. However, it has the second worst routing delay, which is due to the fact that the other MACs have lower PDR and therefore experience less congestion. The best MAC in terms of routing PDR at low packet sizes in this scenario is CSMA/DS. Second to both CSMA/DS and NDMA/DS in PDR is GTDMA, however it has the worst delay due to the large packet sizes dramatically increasing the length of a time slot. Contrastingly, CSMA/DS has the lowest delay of all the MACs, which is also due to the relative length of a packet transmission to the CCA time. The overhead results are very low for all the MACs, with NDMA/DS being the lowest. However, they show a sharp drop and then a general decrease in overhead as the packet size is increased. This is because of the ratio in a packet between the data and the control information; the fraction of the packet that is considered overhead decreases as the amount of data contained within the packet increases. The throughput results show NDMA/DS and CSMA/DS to be the highest, however this is at the expense of energy consumption.

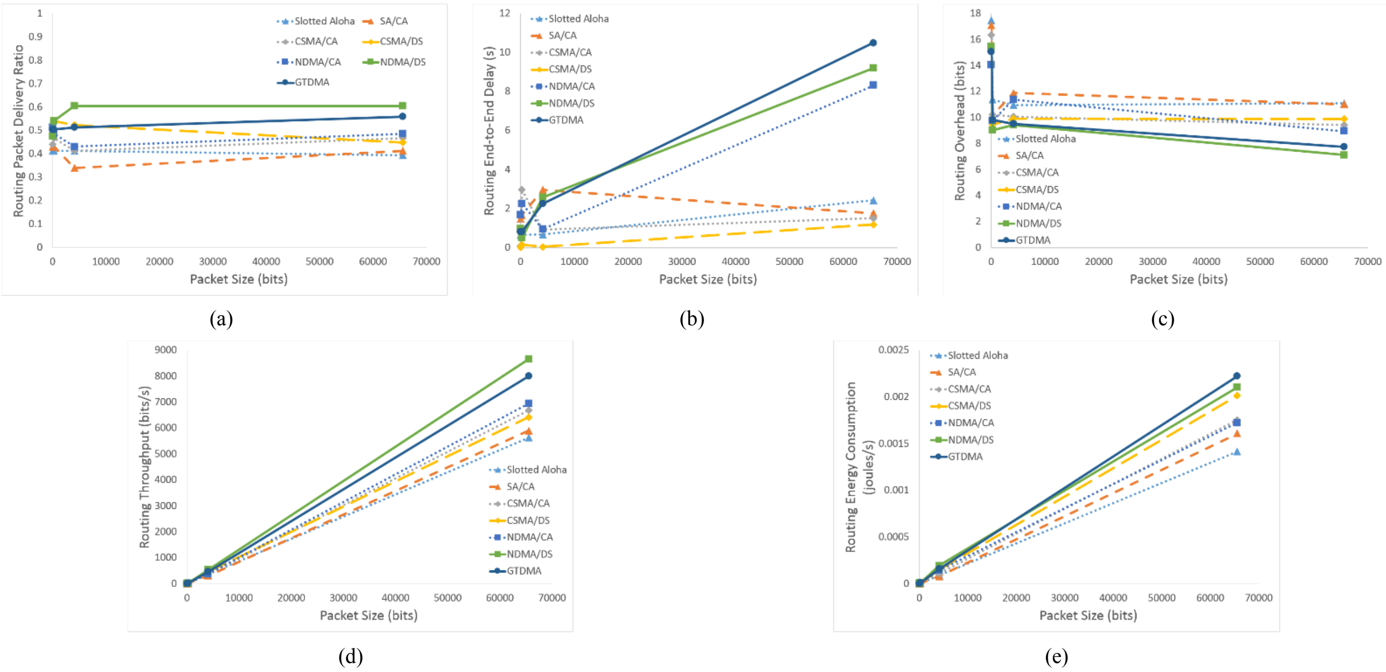


Fig. 8. Routing results using the selected MAC protocols, for varying packet sizes: (a) PDR, (b) Average end-to-end delay, (c) Overhead, (d) Throughput and (e) Average energy consumption.

Overall, these results show how that the GTDMA MAC gives the best performance in high density scenarios with low packet sizes over all traffic levels. However, as the packet size increases, the time slot length also increases and as such the delay incurred by a GTDMA MAC grows dramatically, which subsequently affects the PDR. For this reason, in scenarios with high packet sizes, the proposed NDMA/DS gives better results, due to the ratio of packet transmission time to CCA time and the advantage of spatial reuse allowing multiple simulations to occur simultaneously. GTDMA and NDMA/DS are both collision free, which is beneficial in dense networks and scenarios with large packet sizes, where collisions are likely. However, in scenarios with low densities and low packet sizes, the CSMA/DS protocol gives the best performance. In these situations collisions are less likely, so transmissions are likely to be successful and allow the MAC to perform multiple simultaneous transmissions that are not delayed by long service times. It should also be noted that the large difference between the MAC results and the routing results show how much both the routing and the MAC influence each other. Furthermore, these results highlight the advantage of the proposed NDMA/DS, which is collision free and takes advantage of available location information, and CSMA/DS, which uses small sensing slots to reduce the number of collisions when compared with the commonly used CSMA/CA. Whilst the third proposed protocol, NDMA/CA, does not yield the best overall performance in the presented situations, it does show some promise in the second scenario, in which it tends to perform slightly better than CSMA/CA as well as SA/CA and slotted Aloha.

6. Conclusion

The majority of MWSN MACs are designed to be used with a hierarchical structure, which is not always the best solution for a given application. As such this work evaluated a large variety of alternative MAC layers through simulation, with the aim of determining their suitability for use with flat MWSN protocols. Seven MACs were selected for simulation, including GTDMA from [4], as well as SA and SA/CA to provide a baseline measurement. A modified CSMA/CA was also tested along with the proposed CSMA/DS, NDMA/CA and NDMA/DS. The state-of-the-art routing protocol LASeR was used in the simulations to ensure that the results were representative of a real world scenario, though both MAC and routing metrics were taken.

The three proposed MACs were based on two ideas; dedicated CCA slots and spatial reuse. The dedicated CCA slots allowed the mitigation of local collisions and can be used in conjunction with CSMA to create CSMA/DS. The second idea uses the location information that may be available, to split the network into cells and allow nodes in non-interfering cells to transmit simultaneously. This can then be used with a normal collision avoidance mechanism or the dedicated CCA slots, to create NDMA/CA and NDMA/DS respectively.

The MAC results highlighted GTDMA as one of the best protocols, since it gave the best throughput. However, the routing results demonstrated how it is the combined effect of the routing and the MAC that is important. The routing results suggest that there is not one MAC that is best for every scenario and as such the use of dynamic MAC switching may be beneficial. This could be done using real time measures of the network characteristics to determine which MAC should be used. In the case of LASeR, the GTDMA MAC would be best in high density scenarios with low packet sizes, over all traffic levels. However, in the case of large packet sizes, the preference shifts in favour of the collision free NDMA/DS MAC. Although, in low density environments with low packet sizes, collisions are less likely to occur and as such the CSMA/DS MAC becomes optimal. Overall, GTDMA along with the proposed NDMA/DS and CSMA/DS, give the best performance when paired with LASeR. This shows that there is not always a single MAC protocol, which will perform best in all situations. The wider implication of this work on future MAC design, suggesting that both MAC and routing should be considered together in order to obtain the optimal solution. This approach may be critical in providing communications systems suitable for the next generation of MWSNs.

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